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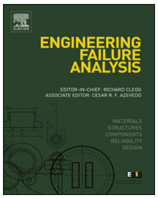

Hydrogen embrittlement behavior of high strength bainitic rail steel: Effect of tempering treatment

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ABSTRACT

The present study was attempted to evaluate the effect of tempering treatment on the hydrogen embrittlement (HE) behavior of a novel bainitic rail steel by using slow strain rate test (SSRT) with notched round bar specimens. The microstructure of the as-hot rolled rail steel mainly consists of granular bainite and ~9 vol% martensite. It was found that tempering treatment could increase the HE resistance and decrease the susceptibility to HE of the as-hot rolled bainitic rail steel except at temper embrittlement temperature of ~400 °C, and excellent HE properties could be obtained when tempered at 500 °C at less expense of strength and ductility. The enhanced HE properties are ascribed mainly to the gradual decomposition of blocky M/A constituents as well as the tempering of the martensite. It is thus suggested that suitable tempering after hot rolling could be applied to enhance the HE properties as well as to obtain maximum mechanical properties, and thus to guarantee the safety of bainitic steel rails in service.

1. Introduction

High C-Mn steels with full pearlitic microstructure have been widely used as rail steels in railway systems because of their superior mechanical properties, which is the primary requirement for withstanding heavy traffic loads [1]. Recently, higher train speeds and increased axle loads to increase the efficiency of rail transport have given rise to larger wheel/rail contact forces [2]. This trend has been increasing the severity of the environment in which rails are used and thus promoting the research and development of next generation rail steels with enhanced properties and longer rail service life [3]. It seems that bainitic steels particular low-C ones have the highest potential to substitute the traditional pearlitic rail steels due to their excellent mechanical properties, such as high strength and toughness as well as excellent fatigue performance [1,4–8].

Bainitic rail steels with strength levels as high as 1200–1500 MPa have been used to manufacture rails and crossings in recent years [6–9]. However, hydrogen related brittle fracture occurred during the process of service of bainitic steel rails and crossings, which is one of the reasons for the limited use of this kind of steel in the past decades [9]. Since bainitic rail steels are of relatively high strength and exposed to conditions that favor hydrogen entry (through corrosion), increasing interests have been paid to their hydrogen embrittlement (HE) behavior [9–12]. Zhang et al. found that the content of hydrogen in the bainitic steel used for crossings played a key role in its failure mechanism; when the hydrogen content is higher than a critical value of ~0.7 ppm, hydrogen-induced brittle fracture was responsible for the failure of the crossings in a short time in service [9]. Zheng et al. reported that the susceptibility to HE significantly decreased with increased Al content in Mn—Al bainitic steels for crossings mainly due to the increased volume fraction of retained austenite (RA) [10]. Li et al. showed that pre-deformation treatment on a carbide-free bainitic steel for

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railway crossings notably increased its HE sensitivity [11]. Our previous research also revealed that the bainitic rail steel was more susceptible to HE than conventional pearlitic rail steel [12]. Therefore, it is necessary and important to further investigate the HE behavior of bainitic rail steel for the purpose of increasing the lifetime and reliability of railway rails and crossings.

The microstructures of commercial bainitic steels which are produced by continuous cooling transformation such as environment-friendly air cooling process after hot rolling/forging are often quite complex compared to those formed from austenite by isothermal transformation. Thus mixed microstructures including granular bainite, lath bainite or even martensite are often found in continuously cooled bainitic rail steels, which influence final mechanical properties through phase type, morphology and size [7,8,12]. It was also reported that bainite/martensite (B/M) multiphase microstructure of bainitic rail steel exhibited superiority to conventional pearlitic rail steel [3,7]. However, the existence of brittle untempered martensite is usually detrimental to the mechanical properties of bainitic steels as well as the non-equilibrium microstructure. In fact, it was found that tempering treatment had significant influence on the mechanical properties of bainitic and B/M multiphase steels [8,13,14]. Therefore, tempering treatment after hot rolling/forging began to be applied to obtain maximum performance as well as to relieve the residual stress and to stabilize phases of bainitic rails [8].

It has been confirmed that suitable tempering treatment is also beneficial to relieve the susceptibility to HE of high strength steels [15–20]. However, there are few published data available concerning the effect of tempering treatment on the susceptibility to HE of bainitic rail steels. Therefore, in the present study, the influence of tempering treatment on the HE behavior of a novel bainitic rail steel was studied by using slow strain rate test (SSRT), in an attempt to enhance the resistance to HE thereby ensuring the reliability of bainitic rail steels.

2. Material and methods

2.1. Materials and specimen preparation

The samples used in the current investigation were obtained from hot rolled and air cooled steel rails produced in actual production line with the chemical composition as listed in Table 1. Specimens were cut from the head region of the hot rolled rails in the rolling direction. The as-hot rolled specimens (designated as B1) were divided into four groups and were then tempered at 280 °C, 350 °C, 400 °C and 500 °C for 2 h, respectively, which were henceforth designated as BT2, BT3, BT4 and BT5 specimens, respectively. Moreover, part of the as-hot rolled specimens were austenitized at 880 °C for 0.5 h, oil quenched and then tempered at 450 °C for 2 h to obtain quenched and tempered (Q&T) microstructure for comparison, these were designated QT4.

Circumferentially notched round bar specimen with notch root radius of 0.15 mm ($K_t = 3.2$) [21] was used for the SSRT as shown in Fig. 1. The presence of a notch allows for obtaining a hydrostatic stress state to increase the embrittling influence of hydrogen. Smooth round specimens for tensile test are standard round bars with 5 mm diameter and 25 mm gauge length. Specimens with diameter of 5 mm and length of 25 mm were used to study the hydrogen desorption behavior. All the specimens were rinsed with deionised water and then degreased with ethanol before hydrogen-charging. Hydrogen was introduced into the SSRT and the thermal desorption spectrometry (TDS) specimens by electrochemical charging in a 0.1 mol/L NaOH aqueous solution at 8 mA/cm^2 current density for 72 h at room temperature to ensure an equilibrium and constant hydrogen content throughout the specimens [20].

2.2. Measurement of HE susceptibility and hydrogen content

SSRT was performed within 10 min after the termination of hydrogen-charging using a WDML-100 kN type uniaxial tensile machine at room temperature with a duration time of about 1.5 h to 2 h. The strain rate was $2.1 \times 10^{-6}\,s^{-1}$ and the test results represent the mean value of at least four specimens. Meanwhile, corresponding specimens without hydrogen-charging were also tested as a reference. After SSRT, the notch tensile strengths (σ_{N0} and σ_{NH} for the uncharged and hydrogen-charged specimens, respectively), which were defined as the nominal maximum tensile stresses, were obtained. HE was evaluated using the so-called HE index (HEI), which was determined by calculating the relative notch tensile strength loss according to the following equation:

$$HEI\,(\%) = \left(1 - \frac{\sigma_{NH}}{\sigma_{N0}}\right) \times 100\% \tag{1}$$

The TDS specimen for the analysis of hydrogen was heated from ambient temperature to 800 °C at a constant heating rate of 100 °C/h, and then the hydrogen effusing out of the specimen was analyzed by the quadrupolar mass spectrometer and the hydrogen content could be obtained through the integration of the hydrogen evolution curve.

Table 1

Chemical composition of the tested bainitic rail steel (wt%).

C	Si	Mn	P	S	Cr	Ni	Mo
0.20	0.80	2.00	0.021	0.010	0.80	0.49	0.31